LOW COST, HIGH AVERAGE POWER, HIGH BRIGHTNESS SOLID STATE LASER

This application is a continuation of application Ser. No. 08/503,373, filed Jul. 17, 1995, now abandoned, which invention is a Continuation-in-Part application of Ser. No. 08/295,283, filed Aug. 24, 1994, now U.S. Pat. No. 5,434,875 on Jul. 18, 1995, Ser. No. 08/339,755, filed Nov. 15, 1994 now U.S. Pat. No. 5,491,707 and Ser. No. 429,589 filed Apr. 27, 1995 now abandoned. This invention relates to laser systems and in particular to high power, high brightness solid state laser systems.

BACKGROUND OF THE INVENTION

There is a growing need for reliable, economical X-ray sources for X-ray lithography. It is known that X-ray sources can be produced by illuminating certain metals with very high brightness laser pulses. Required brightness levels are in the range of 10^{11} to 10^{13} W/cm^2 for projection lithography and 10^{13} to 10^{15} W/cm^2 for proximity lithography.

In a typical X-ray lithography setup, a semiconductor waffer coated with a photoresist and covered at a distance of about 30 to 40 microns with an x-ray absorbing mask is illuminated with a X-rays from a point X-ray source located about 20 to 50 cm from the mask. At about 20 cm the spot size may be in the range of about 100 μm and at about 50 cm the spot size is typically larger, like 300 μm. Spot sizes are chosen to minimize blurring that comes with larger sizes and interference fringes that comes with smaller spot sizes. Current X-ray lithography needs are for resolution of chip features as small as 0.13 micron.

To meet future commercial lithography needs, average laser power requirements are about 500 Watts for projection and 1000 Watts for proximity. In addition the lithography process needs call for an X-ray spot diameter of about a 100 μm to a few 100 μm. Designing a laser to meet these requirements involves solving several current problems. The first is the correction of aberrations due to thermal distortion and self focusing in the laser rod. This problem is currently being dealt with by utilizing a Stimulating Brillouin Scattering (SBS) cell to remove these aberrations. SBS cell materials perform efficiently for laser pulses of several nanoseconds or greater. For nanosecond laser pulses, the energy needed to achieve the required brightness is 10 to 30 Joules per pulse and the repetition rate needed to achieve the required power is 100 to 30 hertz. This high pulse energy design creates two additional problems. The amount of debris produced by nanosecond pulsed lasers focused on solid targets, when operated at the required brightness and power levels, is unacceptable. (Studies done by Rutherford and CREOL indicate that the debris level from metal targets is related to the pulse duration. The shorter the pulse duration the lower the debris level.) There is a research program underway to reduce debris by using solid xenon as an X-ray target, but it is at a very early stage and costs are uncertain. The final problem is the cost of the X-ray lithography system.

Pulses in the nanosecond range when focused for X-ray generation can cause gas breakdown unless the target is located in vacuum chamber. Vacuum chambers add complexity and typically require an X-ray window.

Flash lamp pumped lasers involve high maintenance costs. Maintenance costs can generally be reduced by pumping with diode lasers. Unfortunately, laser diodes required for the 10 joule per pulse 100 Hz lasers costs millions of dollars. Diode pumped solid state laser systems are superior to the currently available commercial lasers in efficiency, reliability, compactness, EMI, acoustic noise and more.

What is needed is a laser system that meets the needs of X-ray lithography to provide 1)high average power and high brightness, 2) low debris levels and 3) low capital and maintenance cost.

SUMMARY OF THE INVENTION

The present invention provides a high average power, high brightness solid state laser system. We first produce a seed laser beam with a short pulse duration. A laser amplifier amplifies the seed beam to produce an amplified pulse laser beam which is tightly focused to produce pulses with brightness levels in excess of 10^{11} Watts/cm^2. Preferred embodiments produce an amplified pulse laser beam having an average power in the range of 1 kW, an average pulse frequency of 12,000 pulses per second with pulses having brightness levels in excess of 10^{14} Watts/cm^2 at a 20 μm diameter spot which may be steered rapidly to simulate a larger spot size. Alternately, several (for example, seven) beams can each be focused to 20 μm and clustered to create effective spot sizes of 100 to 200 μm. These beams are useful in producing X-ray sources for lithography.

In one preferred embodiment, the seed beam is produced in a mode locked Nd:YAG oscillator pumped by a diode array with the frequency of the pulses being reduced by an electro-optic modulator. In a second preferred embodiment, the seed beam is Q switched and includes a Pockels cell for cavity dumping. In a third preferred embodiment, the short duration high frequency pulses for the seed beam is produced by cavity dumping of a short cavity resonator.

A preferred kW system uses a Nd:YAG seed laser to generate 150 ps pulses at a frequency of 1 kHz, the seed beam is amplified in a preamplifier and the amplified beam is split by beam splitters into seven separate beams, each of which are directed to one of seven parallel amplifiers. The output beams of the amplifiers are frequency doubled to 532 nm and each beam is focused to a 20 μm spot on a copper target and the 20 μm spots are clustered to form a larger spot of about 150 μm.

The Applicants experimental results demonstrate good X-ray production with tight focusing on copper and iron targets at focal lengths of about 5 cm of a 72 mJ/p at 532 nm beam produced by frequency doubling a 130 mJ/p 1064 nm Nd/YAG beam. These results indicate that about 10 percent x-ray conversion can be obtained at about 130 mJ/p at 532 nm. No damage to the laser crystal due to self focusing was observed at energy levels (in the crystals) of 250 mJ/p at 1064 nm.

As compared with prior art high brightness lasers, we have achieved our very high brightness by reducing the pulse duration by about 2 or 3 orders of magnitude, from a few ns to 100 ps or less and by focusing on a very small spot. Short pulse duration at low energy per pulse permits focusing the beam in a helium atmosphere at atmospheric pressure. No vacuum chamber is necessary.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a drawing showing the principal features of a preferred embodiment of the present invention for producing high brightness pulse laser beams useful for X-ray lithography.

FIG. 1A, 1B and 1C are qualitative representations of the pulse shape at various stages of the embodiment shown in FIG. 1.